COGNITION IN THE AUTOMATED COCKPIT: A COHERENCE PERSPECTIVE

Kathleen L. Mosier
San Francisco State University
San Francisco, CA

Much of the focus of papers in this symposium has been on using cues in the decision-making environment, input from relevant sources, and knowledge from past experience to assess current situations and make decisions. The cognitive processes inherent in these tasks are critical to success in the aviation environment; however, attention must also be paid to the cognitive requirements for effective diagnosis and decision making within the automated cockpit. Most importantly, in terms of theoretical and practical implications, the sophistication of automated systems in the cockpit means that pilots have access to highly reliable and accurate information (rather than probabilistic cues). This change demands that we examine cognitive processing within the automated cockpit in terms of the match or mismatch between the cognitive behavior elicited by the electronic environment, the cognitive response required by the task, and the cognitive strategy adopted by the pilot. The premise of this paper is that a framework that accomplishes this can be found in *correspondence* and *coherence*, complementary metatheories of judgment and decision making, and in the Cognitive Continuum Theory of judgment (CCT ; e.g., Hammond 1996, 2000; Hammond, Hamm, Grassia, & Pearson, 1997), and that the nature of the pilot's cognitive task in the automated cockpit has been altered from a largely intuitive, correspondence-based task to a primarily analytical, coherence-based task. The purpose of this paper will be to briefly describe these theories and their relevance to diagnosis and decision making in the automated cockpit, and to explore whether the design of automated systems supports or hinders requisite cognitive strategies.

Much of the focus of papers in this symposium has been on using cues in the decision-making environment, input from relevant sources, and knowledge from past experience to assess current situations and make decisions. The cognitive processes inherent in these tasks are critical to success in the aviation environment; however, attention must also be paid to the cognitive requirements for effective diagnosis and decision making within the automated cockpit. The flight control task, once a "stick-and-rudder" process, is today essentially an automation problem involving programming and monitoring skills. The pilot's visual task has evolved from a focus on perception of aircraft position with respect to terrain, obstacles, clouds, etc., to a monitoring of cockpit systems and displays that give this information.

Most importantly, in terms of theoretical and practical implications, the sophistication of automated systems in the cockpit has changed what pilots use to diagnose situations and make decisions. Pilots now operate within an electronic, deterministic world, and have access to highly reliable and accurate information rather than probabilistic cues. This changes the goal of pilot cognition from perception –> response to thinking, judging, and deciding, and demands that we examine cognitive processing within the automated cockpit in terms of the match or mismatch between the cognitive behavior elicited by the electronic environment, the cognitive response required by the task, and the cognitive strategy adopted by the pilot. The premise of this paper is that a framework that accomplishes this can be found in *correspondence* and *coherence*, complementary metatheories of judgment and decision making, and in the Cognitive Continuum Theory of judgment (CCT ; e.g., Hammond 1996, 2000; Hammond et al, 1997), and that the nature of the pilot's cognitive task in the automated cockpit has been altered from a largely intuitive, correspondence-based task to a primarily analytical, coherence-based task. The purpose of this paper will be to briefly describe these theories and their relevance to diagnosis and decision making in the automated cockpit, and to explore whether the design of automated systems supports or hinders requisite cognitive strategies.

COGNITIVE STRATEGIES: CORRESPONDENCE/COHERENCE

Correspondence.

The goal of correspondence in cognition is empirical, objective *accuracy* in human judgment. *Correspondence competence* refers to an individual's ability to accurately perceive and respond to *multiple fallible indicators* in the environment (e.g., Brunswik, 1956; Hammond & Stewart, 2001). Correspondence judgments cannot be made without reference to the "real world," and are evaluated according to how well they represent, predict, or explain objective reality. A pilot, for example, exercises correspondence competence when using cues outside the cockpit to figure out aircraft position, or to judge height and distance from a runway in order to know when to begin the descent for landing.

Wickens and Flach (1988) incorporated the notion of uncertainty into their model of pilot decision making. They proposed that the pilot must deal with multiple probabilistic cues, such as visual landmarks, smells (e.g., of smoke), aural messages, more-or-less reliable instruments, etc., in assessing the state of the world. "The cues used for situation assessment may be unreliable (e.g., a weather forecast predicts a 20% chance of thunderstorms), and the projected consequences of an action into the future are uncertain" (p. 127). They cited one source of pilot correspondence error, or inaccurate empirical judgments, as the tendency to respond inappropriately to cues - that is, to treat all cues as though they have equivalent reliability and validity, or to utilize cues according to their salience rather than their reliability or validity. "Good" pilot decision makers learn, however, to use these probabilistic cues effectively to make accurate assessments and predictions.

The emphasis of correspondence theories is on the objective correctness of human judgment and the factors that influence it. The decision maker makes a judgment or prediction based on cues or indicators in the environment, all of which are fallible to some degree. The ultimate test of the process is the empirical accuracy of the resultant judgment.

Coherence.

The goal of coherence in cognition, on the other hand, is *rationality* in judgments and decisions. *Coherence competence* refers to an individual's ability to maintain logical consistency in diagnoses, judgments, or decisions. Coherence judgments can be made without direct reference to cues in the "real world" (the pilot never even has to look out the window) – what is important is the logical consistency, or coherence, of the process and resultant judgment. A pilot exercises coherence competence when scanning the information displayed inside the cockpit to ensure that system parameters, flight modes, and navigational displays are consistent with what should be present. What the pilot strives for is a rationally "good" picture - engine and other system parameters should be in sync with flight mode and navigational status - and decisions that are consistent with what is displayed. In contrast to correspondence competence, the quality of the cognitive process utilized is the sole evaluative criterion for coherence.

Much of the research on coherence in judgment and decision making has focused on the difficulty humans have maintaining coherence. Researchers in heuristics and biases, for example, have compared human judgment, which they have found to be characterized by various heuristics (short-cuts) that individuals use to speed up the decision-making process, against normative or mathematical models (e.g., Tversky & Kahneman, 1974; Kahneman, Slovic, & Tversky, 1982). The key issue in terms of this theoretical approach is not whether heuristics may result in accurate judgments, but rather the notion that they exemplify the flawed nature of the human judgment process. Most of the biases individuals exhibit in decision making are the result of non-coherent judgment processes – not using data in a rational and consistent way. *Automation bias*, for example, describes a flawed, non-coherent decision process in aviation characterized by the use of automated information as a heuristic replacement for vigilant information seeking and processing (e.g., Mosier, Skitka, Dunbar, & McDonnell, 2001; Mosier, Skitka, Heers, & Burdick, 1998; Skitka, Mosier, & Burdick, 1999).

COHERENCE IN THE ELECTRONIC COCKPIT

In modern, high-tech aircraft, the flying task is to a very great extent coherence-based. In contrast to earlier pilots, glass cockpit pilots can spend relatively little of their time looking out the window, and most to all of it focused on information inside the cockpit. The data that they utilize to fly can, in most cases, be found on cockpit display panels and CRTs. These data are qualitatively different from the cues used in correspondence judgments. They are *data*, rather than *cues* - that is, they are precise, reliable indicators of whatever they are designed to represent. When crews achieve coherence in the cockpit – for example, when ALL information inside the cockpit paints a consistent picture of the aircraft on the glide path – they have also achieved correspondence, and can be confident that the aircraft IS on the glide path. The pilots do not need to look out the window for airport cues to confirm it, and, in fact, visibility conditions often do not allow them to do so. The cockpit is a *deterministic*, rather than a *probabilistic* environment, in that the uncertainty has, for most practical purposes, been engineered out of it through high system reliability.

This shift in cognitive goals means is that we need to re-examine cognition in the automated cockpit to determine what is required to achieve, maintain, recover coherence in the cockpit, and whether or not these processes are supported by current displays of information. Perhaps the most critical factor impacting pilot ability to achieve and maintain coherence in the cockpit is the degree of match or mismatch between the cognitive tactics elicited by task and display features, and what is required for coherence.

COGNITIVE TACTICS: INTUITION -- > ANALYSIS

Cognitive tactics to achieve coherence and correspondence range from *intuition -- > analysis*. According to CCT, intuition and analysis represent the endpoints on a continuum of cognitive activity (Hammond, 1996; 2000). *Analysis* refers to a "step-by-step, conscious, logically defensible process," whereas *intuition* typically describes "the opposite - a cognitive process that somehow produces an answer, solution, or idea without the use of a conscious, logically defensible, step-by-step process" (Hammond, 1996, p. 50). Judgments vary in the extent to which they are based on intuitive or analytical processes, or some combination of both. During the judgment process, individuals may move along this continuum, oscillating between intuition and analysis - or stopping at points on the way. They may shift between intuitive and analytical strategies many times within the same problem (Hamm, 1988).

Processes described by any point on the continuum may be used to achieve correspondence or coherence. Pilots, for example, may achieve correspondence (accuracy) *analytically*, by using a combination of cues, rules and computations to figure out when to start an approach. Pilots also learn to use *intuitive*, pattern-matching processes to assess cues and judge situations. As they gain more experience, the correspondence process becomes more recognitional, and their *intuitive* assessment of whether the situation "looks right" to start down becomes increasingly effective. In the naturalistic environment, a pilot's correspondence competence – that is, the ability to utilize probabilistic cues in the environment to assess situations and predict outcomes - increases with expertise. Expert pilots are able to quickly recognize a situation, and may be able to use intuitive processes under conditions that would demand analysis of a novice (see Figure 1).

The design and display of most automated systems elicits *intuitive* cognition. Data in the electronic cockpit are pre-processed, and presented in a format that allows, for the most part, a wholistic view of aircraft and system states. Often,

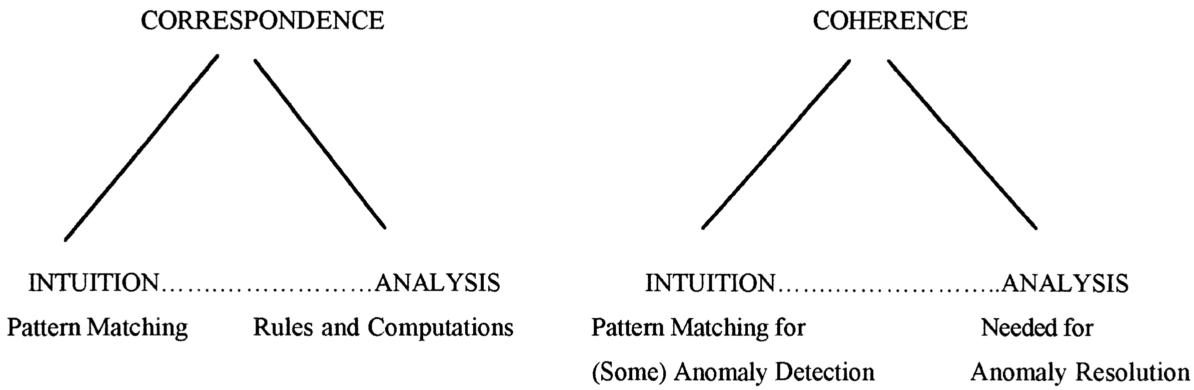

Figure 1. Cognitive tactics to achieve correspondence and coherence in the cockpit.

pictorial representations exploit human intuitive pattern-matching abilities, and allow quick detection of out-of-parameter system states. This design philosophy seems to be consistent with the goals of workload reduction and information consolidation - and, indeed, many features of cockpit displays do foster the quick detection of disruptions to a coherent state. However, current displays may in fact be leading pilots astray by fostering the assumption that cockpit data can be managed in an intuitive fashion. This is a dangerous assumption - one that has not been empirically confirmed.

Within the electronic cockpit, pilots are required to demonstrate coherence competence; that is, to think logically and analytically about data and information in their work environment. This involves knowing what data are relevant, integrating ALL relevant data to come up with a "story" of the situation, and ensuring that the story that the data present is rational and appropriate. It also entails recognizing inconsistencies in data that signal lack of coherence, as well as understanding the limits of coherence-based systems and recognizing their strengths and inadequacies. In some cases, for example, coherence systems will warn you of violations – being too low on glide slope – but in other cases, they won't – going too fast under 10,000 ft.

Many if not most pilot errors in electronic cockpits are failures to detect a disruption in coherence - that is, something in the electronic "story" that is not consistent with the rest of the picture. Although pilots can intuitively infer coherence among cockpit indicators much of the time if things are operating smoothly, repairing - and often detecting - disruptions to coherence demands a shift toward *analysis*. The complex nature of the automated cockpit requires that the detection and resolution of many errors and anomalies, such as being in the incorrect flight mode, be accomplished via analytical means. Within the seemingly "intuitive" displays reside numerical data, for example, that signify different commands or values in different modes. When dealing with coherence disruptions, these data must be interpreted - what does this piece of data mean when shown in this color, in this position on the screen, in this flight configuration, in this mode of flight? Once interpreted, data must be compared with expected data to detect discrepancies, and, if they exist, analysis is required to resolve them before they translate into unexpected or undesired aircraft behaviors.

Moreover, before system data can be analyzed, it must first be located. This is often not an easy process, because as the aircraft cockpit has evolved, much of the systems information has either been altered in format or buried below surface displays. The data that would allow for analytic assessment of a situation may not only not be obvious, but not be presented at all or may be buried below surface features. What the pilot sees is an apparently simple display that masks a highly complex combination of features, options, functions, and system couplings that may produce unanticipated, quickly propagating effects if not analyzed and taken into account (Woods, 1996).

The cognitive processes required in high-tech aircraft, then, are quite different than those needed in early days of flying. Achieving and maintaining coherence competence involves data, rationality, logic, and requires the pilot to move toward the *analytical* modes on the cognitive continuum. This movement affords potential gains as well as potential risks. Analysis in the electronic milieu, as in other arenas, can produce judgments that are much more precise than intuitive judgments. Once the correct landing information is selected and entered into the system, for example, the aircraft can follow an exact three-dimensional path to the runway. However, the analytical process is also much more fragile than intuitive processes - a single small error can be fatal to the process, and one small detail can destroy coherence. Mode confusion, for example, often results from what looks, without accurate analysis, like a coherent picture. The cockpit setup for a flight path angle of -3.3° in one mode looks very much like the setup for a -3300 ft/min approach in another mode. The proliferation of display characteristics such as this indicates that achieving coherence in the glass cockpit is no easy task.

Expertise, moreover, does not offer the same advantages to the pilot in the electronic world as in the naturalistic world. It may, in fact, be counterproductive if accompanied by the tendency to rely on electronic data and systems in an intuitive manner (e.g., Mosier et al., 1998). Experience can also work against a pilot, in that it may induce a "false coherence," or the tendency to see what is expected rather than what is there. Experience may give pilots hints on where to look for anomalies, but it does not insulate them from the need to analyze their way back to coherence. Experts that do think they can operate intuitively in the electronic cockpit are susceptible to the kinds of automation-related errors often discussed by researchers - such as mode errors or automation bias.

IMPLICATIONS FOR PILOT DECISION MAKERS AND COCKPIT DISPLAYS

Examining cognition in the cockpit in terms of a correspondence/coherence framework has practical implications for pilots and for displays. In aviation research, the organizing principles of coherence/ correspondence, intuition --> analysis can be utilized as theoretical frameworks within which to examine pilot cognition and the cognitive requirements of the automated cockpit, and to ensure a match between them. Within these frameworks, we need to develop new ways of thinking about system design and display features, pilot judgment and decision making, and research paradigms and goals.

With respect to the pilots, it must be recognized that correspondence competence and coherence competence are very different abilities - and skill in one does not necessarily guarantee skill in the other. Pilot training programs have in recent years recognized the importance of correspondence competence, and have moved toward naturalistic models of the pilot decision-making process and the impact of expertise. These models have focused on correspondence competence - the ability to recognize probabilistic cues in a dynamic environment, to quickly assess the situation, and to accurately predict the outcome of decisions and actions.

Training for intuitive correspondence competence, however, is not sufficient. It is important also to recognize the importance of coherence competence in the electronic cockpit, and to include training for it. This process demands more than attention and vigilance - it entails the rational, consistent use of information in diagnosis and decision making. Our preliminary work investigates information search and information use as described in ASRS incident reports, in order to track pilot processes utilized to achieve coherence and/or correspondence, and factors associated with success or failure in each.

With respect to display design in the context of coherence demands in the automated cockpit, it is clear that displays should not only support intuitive processes, such as the quick detection of some out-of-parameter states, but must also provide the information necessary for analysis. Woods (1996) referred to automation in electronic cockpits as characterized by "apparent simplicity, real complexity." His characterization might be modified to describe the cognitive processes demanded by automation in electronic cockpits as "apparently intuitive, really analytical." Currently, the mismatch between cognitive requirements of the electronic cockpit and the cognitive strategies afforded by systems and displays makes it extremely difficult to achieve and maintain coherence in the cockpit. On one hand, system displays and the opacity of system functioning foster intuition and discourage analysis; on the other hand, the complexity of automated systems makes them impossible to manage intuitively, and requires analytical processing. Recognition of this mismatch is the first step toward rectifying it.

A second step entails acknowledging that the electronic cockpit is a coherence-based, deterministic world. This means that developers have to design systems that are not only reliable in terms of correspondence (empirical accuracy), but are also interpretable in terms of coherence. Principles of "human-centered automation" prescribe that the pilot must be actively involved, adequately informed, and able to monitor and predict the functioning of automated systems (Billings, 1996). To this list should be added the requirement that the design of automation and automated displays elicits the cognition appropriate for accomplishing the human role in the human/ automation interaction.

If the pilot is expected to maintain coherence in the cockpit, he or she must be able to develop accurate mental models of system functioning. In order to track system status and resolve anomalies, the electronic world must support the analysis of current states and resolution of discrepancies. Additionally, it is critical to design systems that will aid human metacognition - that is, help pilots to recognize when they are utilizing intuitive processes, when these processes are inappropriate, and when and how to accomplish the shift toward analytical cognition.

Coherence in the electronic cockpit is both attainable and maintainable; however, discovering the most effective means to accomplish this requires a shift in our own cognitive activity, as researchers, toward the models and research paradigms that will allow us to more accurately understand behavior in this milieu. Examining cognition within the correspondence/ coherence, intuition -- > analysis framework offers the possibility of finding solutions across automated cockpit problems. By doing this, we will gain a much broader perspective of the issues and potential problems or hazards within the automated environment, and the ability to make informed predictions regarding pilot behavior and cognitive decision-making processes.

ACKNOWLEDGMENTS

Special thanks to Ken Hammond, the coherence/ correspondence guru, whose writings have profoundly influenced this work. A more comprehensive version of this paper has been submitted for publication in *Advances in Human Performance and Cognitive Engineering Research*.

REFERENCES

Brunswik, E. (1956). *Perception and the representative design of psychological experiments.* Berkeley, CA: University of California Press.

Hamm, R. M. (1988). Moment-by-moment variation in expert's analytic and intuitive cognitive activity. *IEEE Transactions on Systems, Man, and Cybernetics, 18(5)*, 757-776.

Hammond, K. R. (1996). *Human Judgment and Social Policy*. New York: Oxford Press.

Hammond, K. R. (2000). *Judgments under stress.* New York: Oxford Press.

Hammond, K. R., & Stewart, T. R. (2001). *The essential Brunswik: Beginnings, explications, applications.* NY: Oxford University Press.

Hammond, K. R., Hamm, R. M., Grassia, J., & Pearson, T. (1997). Direct comparison of the efficacy of intuitive and analytical cognition in expert judgment. In W. M. Goldstein & R. M. Hogarth (Eds.), Research on judgment and decision making: Currents, connections, and controversies (pp. 144-180). Cambridge: Cambridge University Press.

Kahneman, D., Slovic, P., & Tversky, A. (Eds.). (1982). *Judgment under uncertainty: Heuristics and biases.* Cambridge: Cambridge University Press.

Mosier, K. L., Skitka, L. J., Dunbar, M., & McDonnell, L. (2001). Air crews and automation bias: The advantages of teamwork? *International Journal of Aviation Psychology, 11*, 1-14.

Mosier, K. L., Skitka, L. J., Heers, S., & Burdick, M. D. (1998). Automation bias: Decision making and performance in high-tech cockpits. *International Journal of Aviation Psychology, 8*, 47-63.

Skitka, L. J., Mosier, K. L., & Burdick, M. (1999). Does automation bias decision making? *International Journal of Human-Computer Studies 50*, 991-1006.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science, 185*, 1124-1131.

Wickens, C.D., & Flach, J. M. (1988). Information processing. In E. L. Wiener & D. C. Nagel (Eds.), *Human factors in aviation*. San Diego, CA: Academic Press. (pp. 111-156)

Woods, D. D. (1996). Decomposing automation: Apparent simplicity, real complexity. In R. Parasuraman, & M. Mouloua (Eds.), *Automation and human performance: Theory and applications.* New Jersey: Lawrence Erlbaum Associates. (pp. 3-18)